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HybriDrive® Propulsion System

Cleaner, smarter power for Medium & Heavy Duty Vehicles

"Mechanical, thermal and packaging challenges of high voltage, high power electronics for heavy duty propulsion and power management applications."

APEC Conference 2012

By Stephen Kosteva
Chief Engineer, Mechanical Systems- Hybrid Solutions

Drivers of Hybrids in Medium to Heavy Duty Vehicle Markets

Governmental Policies and Regulations

- Energy Policies.
- Positive Environmental Impacts (lower emissions).

Green Image

- Social Conscience.

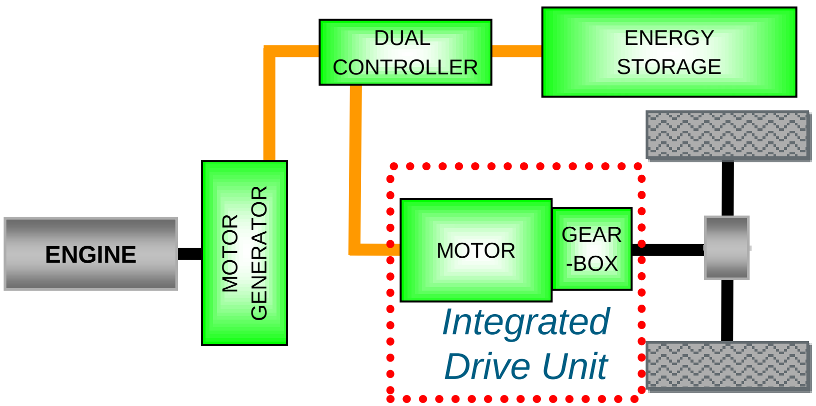
Payback

- *Payback is a function of*
  - ✓ Fuel Prices.
  - ✓ Acquisition Cost.
  - ✓ Fuel Economy (System Performance).
  - ✓ Reliability & Maintenance Costs (Operational & Life Cycle Costs).

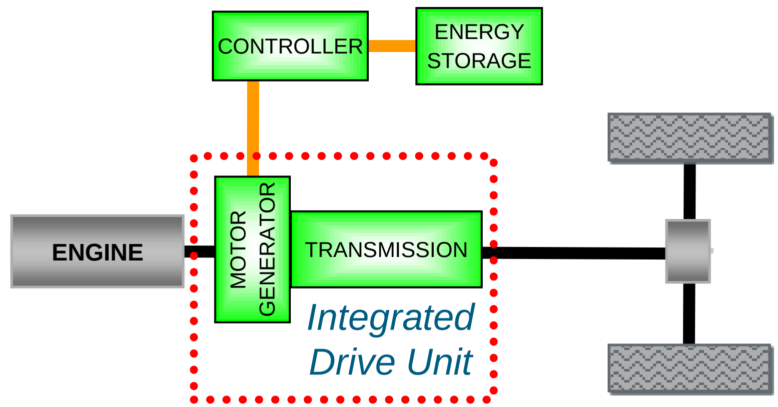
Fleet Operators prefer a < 5 Year Payback

Most Common Hybrid Architectures – series vs. parallel

Series Hybrid Drive Train



Parallel Hybrid Drive Train



Electric Interconnect

Mechanical Interconnect

- Sized for full all-electric mobility
- No mechanical coupling of engine to road enables maximum control over engine operation
- Applicable for fuel cell or battery powered vehicles
- Ideal for urban Transit Buses

- Sized for desired braking energy capture
- Engine still mechanically coupled to road; enables higher efficiency at highway speeds
- Scalable for a wide range of duty cycles
- Ideal for trucks

Architecture choice dependent on application, vocation and duty cycle

Major Design Requirements Differences between Automotive to Heavy Duty Vehicles

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❑ Manufacturing Volumes

Buses Trucks Automobiles

❑ Life and Reliability Requirements

- ➢ Longer life and more operating hours
- ➢ More aggressive duty cycle

Major Differences Have Significant Cost Impacts & Drive Very Distinct Design Philosophies

Major Design Requirements Differences between Automotive to Heavy Duty Vehicles (cont)

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❑Environmental Requirements

- ➢ More Mounting Location Options
- ➢ Higher Vibration Requirements
- ➢ Tighter Sealing and Humidity Requirements
- ➢ Direct Solar Exposure
- ➢ Larger Temperature Variations

❑ Power and Size Requirements

- ➢Larger vehicle weight requires more power
- ➢Higher power means more current and more heat dissipation
- ➢Higher Voltage/Current/Heat drives Package Size
  - ➢ Connectors, Capacitors, Bus-bars, Switches, Cables , Energy Storage, etc

Major Differences Have Significant Cost Impacts & Drive Very Distinct Design Philosophies

Life and Reliability Requirements

Automobiles

- 10 years
- 125,000 miles
- 6000 hours

Medium & Heavy Duty Trucks

- 12-15 years
- 250,000 – 300,000 miles
- 22,500 hours

Transit Buses

- 15+ years
- 500,000 miles
- 52,000 hours

Heavy Duty Vehicles Have Much Higher Hours of Operation per Service Life

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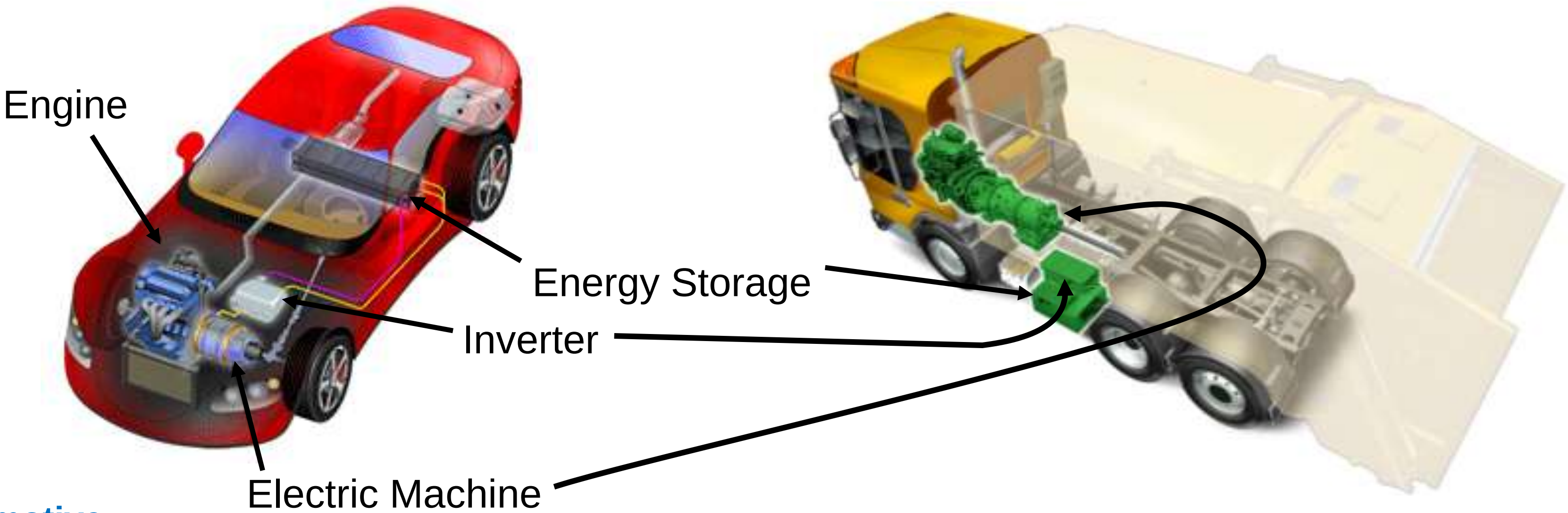
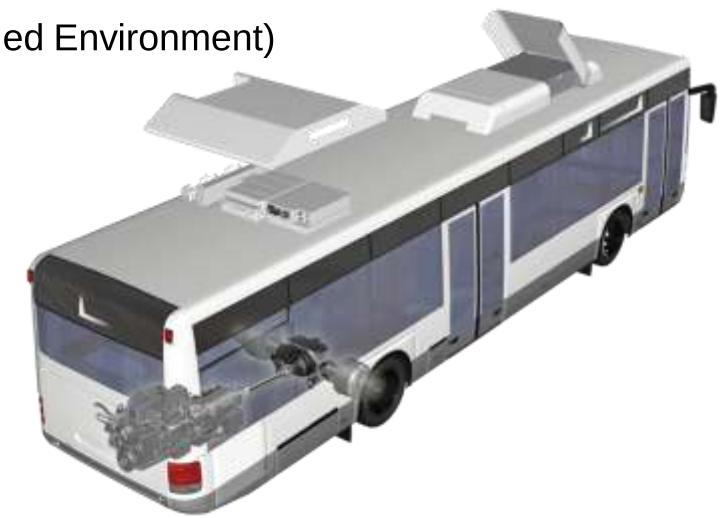
Heavy Duty System Layouts vs. Automotive Layouts



Automotive:
- ESS and Control located in Passenger Compartment (Controlled Environment)
- Inverter and Transmission under hood

Trucks and Buses:
- Components not located in passenger compartments
- More location options (OEM dependent)
  - Frame Rails
  - Roof
  - Rear Cab
  - Engine Compartments
  - etc



Different Mounting Options Opens Environmental Design Aperture

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Governing Performance Specifications and Power Levels

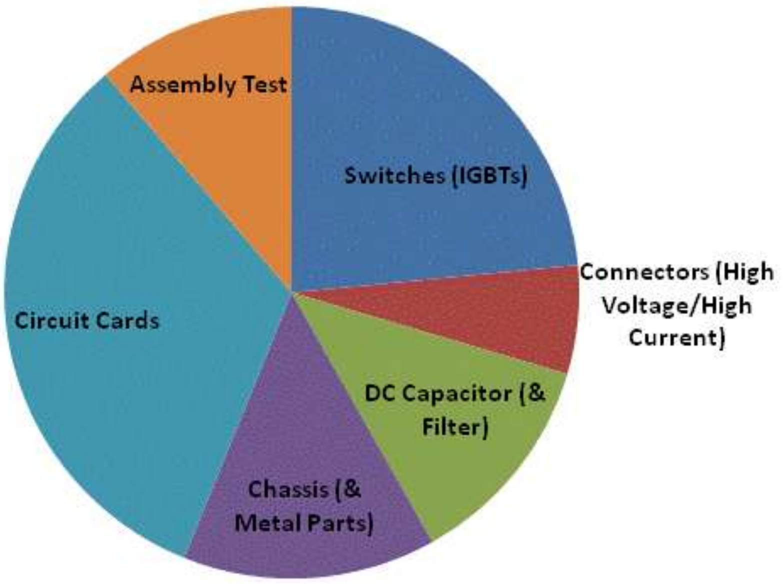
	Power & Torque Levels	Performance Requirements	Environmental Requirements
	30-65 kW ~250 Nm Crankshaft	OEM Specific	OEM Specific
	70-120 kW 800 Nm Crankshaft	OEM Specific Vocation & Duty Cycle Specific	SAE J1455 ISO 16750
	150- 250 kW (motor) 150- 250 kW (Gen) 6900 Nm DriveShaft	White Book (USA)	SAE J1455 ISO 16750

Understanding Propulsion Torque & Power Requirements and Operational Duty Cycles are Key to a Robust & Viable Heavy Duty Solution

Packaging Cost Challenges for Heavy Duty Hybrid Power Electronics

Medium/Heavy Duty Commercial Vehicle Inverter
Relative Component Cost Breakdown

Pennies Still Count



With the Increase in Performance, Size, Duty Cycle, Life and Reliability Requirements,
How do we meet the aggressive cost targets
of a 5 year or less payback for trucks?

Focus on the Key Cost Driving Components

Insulated Gate Bipolar Transistor (IGBT) - Single Highest Cost Component

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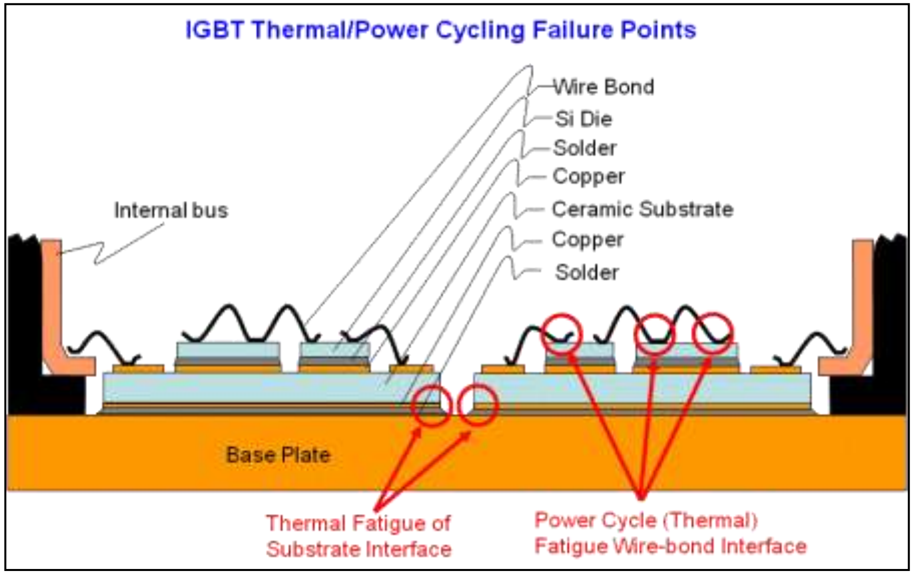
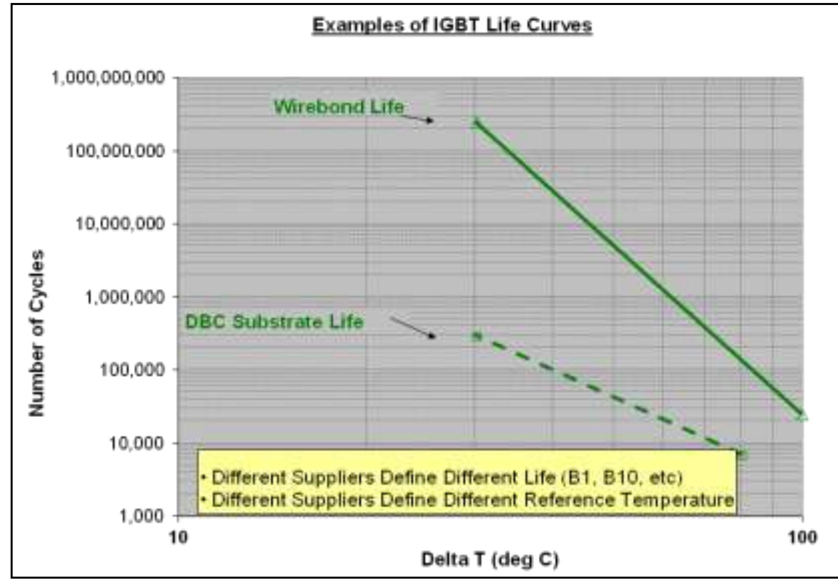
Known Wear Out Mechanisms





Less Silicon

Lower Switch Costs
Higher Power Density
Lower Life
Costly cooling system

TRADE

More Silicon

More Cost
Lower Power Density
Longer Life
simpler cooling system

Optimize Silicon of Switching Devices (IGBTs)

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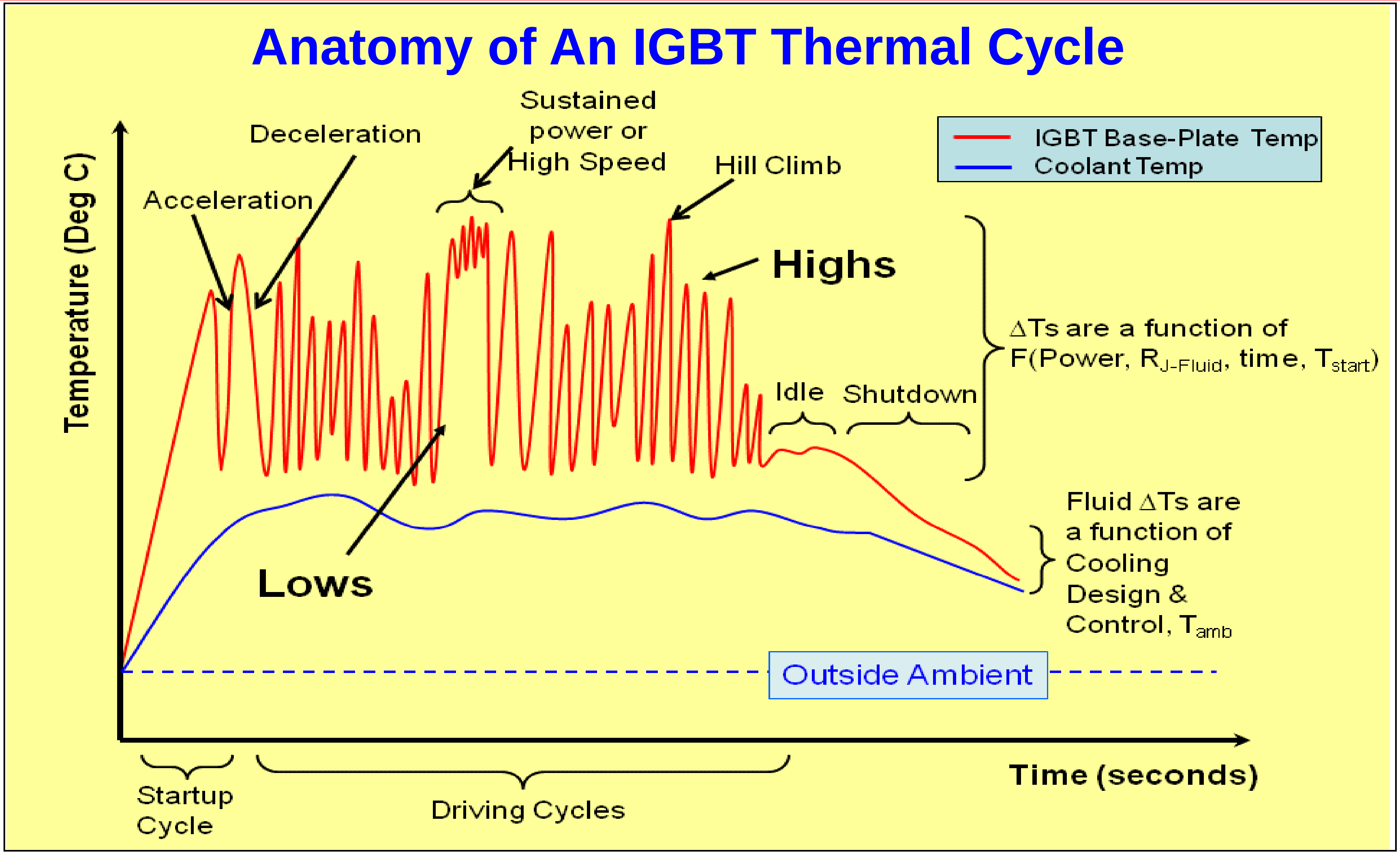
Insulated Gate Bipolar Transistor (IGBT) – LIFE & DUTY CYCLE



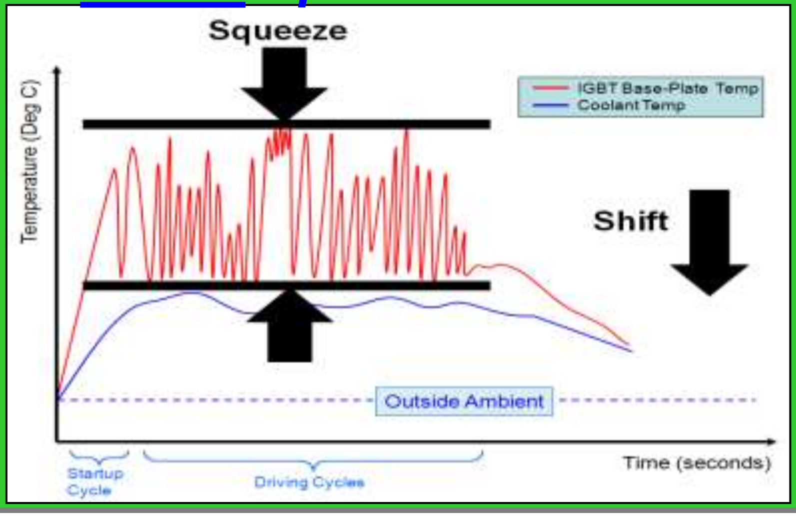
Inverter Switch Life is Dependent on Vocation, Duty/Drive Cycle, Driver Habits, Cooling System

Insulated Gate Bipolar Transistor (IGBT) – Life Prediction Tool

❑ Life Prediction Tool Created:

- Transient Thermal Model (Simplified Representation)
    - Foster vs. Cauer Model (simplicity vs physical meaning)
- Real Time Prediction of Junction and Substrate Temperatures Profiles
- Cycle Counting
- Life Damage Predictions
- System Optimization for DT

Goal: *Squeeze & Shift*

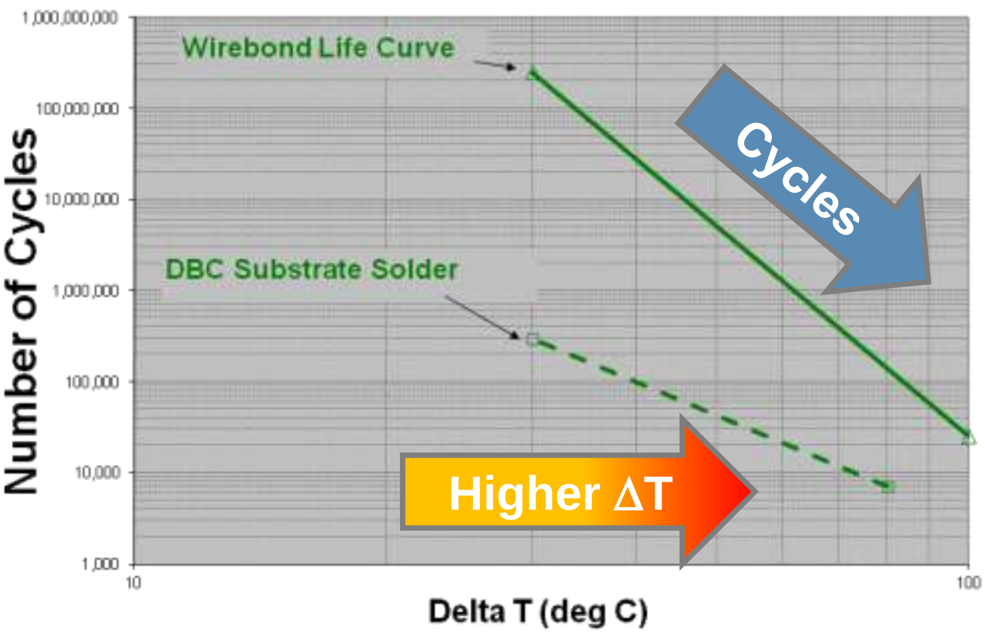


Can Be Adapted for On board Real Time Life Prognostics

Insulated Gate Bipolar Transistor (IGBT) - Opportunities for IGBTs

- **Higher Temp Silicon Carbide**
- **New Packaging**
  - Double Sided Cooling
  - New Materials
  - No Wire-bonds

Examples of IGBT Life Curves

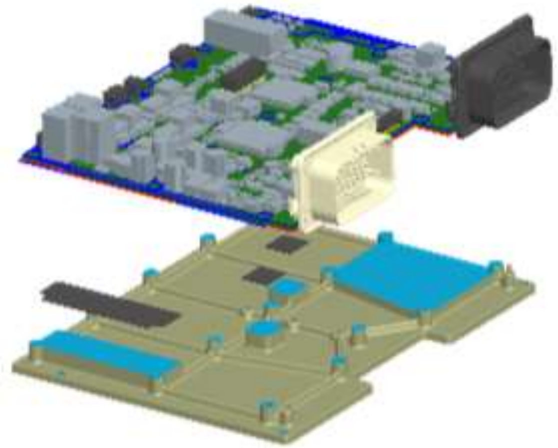


Higher Junction temperatures alone in SiC can reduce overall life
➔ Need to be able to raise inlet

- **Also Need Higher Temperature…**
  Film Caps, Circuit Card Components, Current Sensors, Connectors, etc.

Higher Temperature SiC ➔ Itself is Not the Answer

Circuit Card Cost Opportunities – Lower Costs CCAs



❑ Limit the number of Circuit Cards

- ➢ Reduces interconnect
- ➢ Increases reliability
- ➢ Less chassis mounting features

❑ Limit size of circuit cards

- ➢ "Just Enough" Function
- ➢ Combine Control Function (Motor Control and System Control)

❑ Leverage high volume automotive component cost

- ➢ Automotive components are typically lower temp.

❑ Combine vibration support with thermal support

- ➢ Analysis tools to predict life of solder joints
- ➢ Low Cycle Fatigue (temperature)
- ➢ High Cycle Fatigue (vibration)

Heavy Duty Vehicles Have Much Higher Hours Operation per Service Life

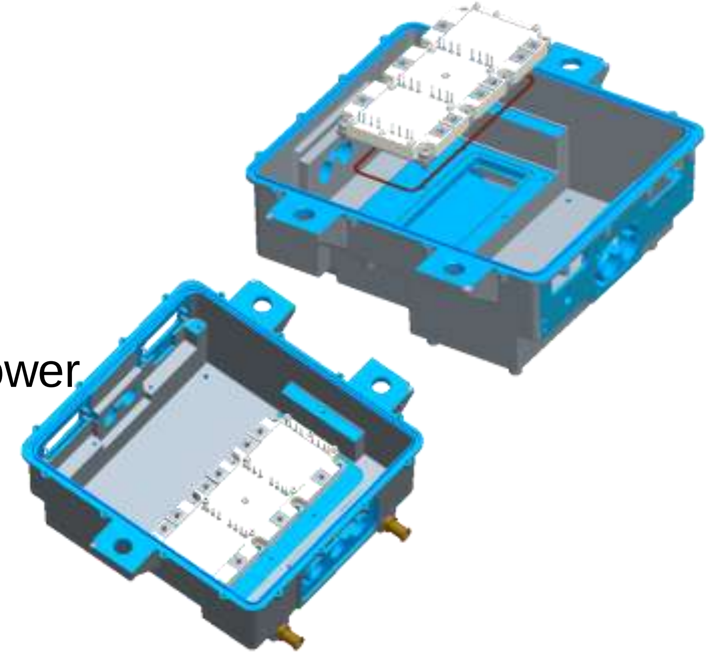
Chassis Cost Opportunities – Lowering Metal Costs

❑ Direct water cooled IGBTs simplify Chassis

- ➢ Low cost castings
- ➢ Less machining

❑ Size Matters

- ➢ Smaller size lowers Material cost ($/lb)
- ➢ Less coring, tooling, handling, finishing, etc



❑ Use Common Hardware

- ➢Less time on costing machining tools

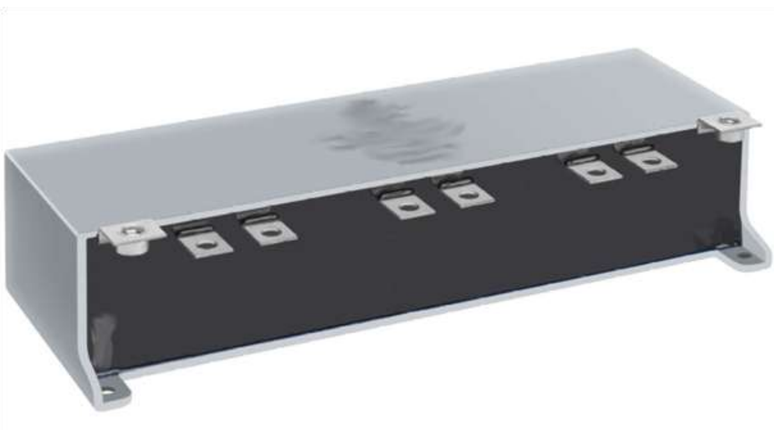
❑High Voltage/ High Current Connectors

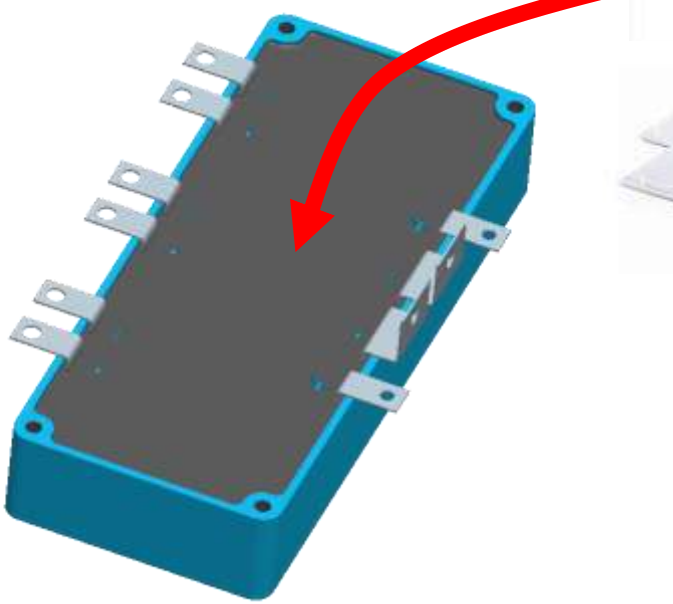
- ➢Pluggable connectors simplify chassis but lower reliability.

Heavy Duty Vehicles Have Much Higher Hours Operation per Service Life

DC-Link Capacitor & Filter Opportunities

- ❑ Laminating bus work is expensive
- ❑ Custom caps can be tailored:
  - ➢ Less chassis machining
  - ➢ Shaped for easier low cost assembly
  - ➢ Molding replaces expensive laminating on bus work





Custom DC-Link Filters Provide Compactness, Isolation and Ease of Assembly

High Voltage High Current Connector Considerations

- ❑ **Connector Type**
  - ➢ Bolted (ring terminal)
  - ➢ Pluggable Connector

- ❑ **Voltage Isolation**
  - ➢ creepage / clearance

- ❑ **Current Carrying Capacity**
  - ➢ ~200A – 350 Arms (Parallel commercial vehicles)
  - ➢ ~700 – 1000 Arms (Series Transit Vehicles)

- ❑ **IP Ratings**
  - ➢IP6K9K & IP67

- ❑ **Shield Terminations & Interlocks**
  - ➢ Isolated & Low impedance

Low Cost COTS Connectors do not exist for Heavy Duty Vehicle Apps

Standard Metrics – The Ratings Game

Common Electronics Performance Metrics

- Cost → $/kW
- Power Density → kW/L
- Specific Power → kW/kg
- kVA

Other Variables

- Operating Voltage
- Efficiency
- Switching Frequency
- Control (machine or system control included)
- Peak Power vs Continuous Power
- At What Environmental Conditions
  - Ambient
  - Coolant Temperature
- Design Life/Duty Cycle

Need For Common Ratings Definitions

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Summary

- Major differences between ***automotive*** and ***heavy duty*** applications have significant cost impacts & drive very distinct design philosophies for power electronics .

- Commonly used Inverter Metrics ($/kW, kW/kg) don't embody the differences.

- Aggressive cost pressures still exist as ***payback*** is critical to OEMs and fleet operators.

- ***IGBT optimization*** is key to managing inverter costs with higher power/torque requirements and more aggressive duty cycles.

- Combining function (***building block approach***) helps reduce costs by lowering part costs, assembly cost, and interconnect costs.

Mechanical, thermal and packaging challenges of high voltage, high power electronics for heavy duty propulsion and power management applications.

BAE SYSTEMS

HybriDrive®

Series propulsion system

Transit Bus

Parallel propulsion system

Medium & Heavy Duty

Commercial Trucks

Questions?